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STUDIES OF PERFORMANCE IN COMPLEX AIRCREW TASKS

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13. ABSTRACT

The basic objective of the research described in this report was the investigation of human performance under conditions of divided attention. The requirement to divide attention between multiple information sources is placed on the operator of many modern man-machine systems. For example, performance under such conditions is normally required in the operation of an aircraft or in the process of controlling air traffic from the ground.

Our research during the period of this grant has focused on performance in two types of divided attention paradigm, referred to as the sequential and simultaneous demand paradigms. In a simultaneous demand situation, the operator is required to process at least two sources of information simultaneously. The sequential demand situation requires rapid alternation between at least two sources of information. Our research on the simultaneous demand situation centered on performance when a memory task was time-shared with a pursuit tracking task similar in principle to a vehicular control task. These experiments showed a) that decrements occur in both tracking and retention performance, b) that these decrements increase with signal complexity on the tracking task and acoustic similarity on the memory task, and c) that practice reduces these decrements by an amount proportional to the size of the initial decrement. Other experiments showed that in the simultaneous demand paradigm, the S is capable of allocating capacity across multiple input sources in proportion to the expected value of each source's information.

Experiments on sequential demand time-sharing focused on two basic situations. First were situations characterized by heavy memory loads and interstimulus intervals between 1 and 8 seconds. Second were situations involving low memory loads and interstimulus intervals between .1 and 1.0 seconds. In both situations, a time-sharing decrement occurs and is proportional to the interstimulus interval.

The time-sharing decrements observed in both simultaneous and sequential demand situations were found to be primarily localized in stimulus encoding and the process of transferring information from long-term to short-term memory.

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STUDIES OF PERFORMANCE IN COMPLEX AIRCREW TASKS

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

INTRODUCTION

The basic objective of the research described in this report was the investigation of human performance under conditions of divided attention. The requirement to divide attention between multiple information sources is placed on the operator of many modern man-machine systems. For example, performance under such conditions is normally required in the operation of an aircraft or in the process of controlling air traffic from the ground.

Our research during the period of this grant has focused on performance in two types of divided attention paradigm, referred to as the sequential and simultaneous demand paradigms. In a simultaneous demand situation the operator is required to process at least two sources of information simultaneously. The sequential demand situation requires rapid alternation between at least two sources of information. Our research on the simultaneous demand situation centered on performance when a memory task was time-shared with a pursuit tracking task similar in principle to a vehicular control task. These experiments will be described first.

TIME SHARING IN THE SIMULTANEOUS DEMAND PARADIGM

GENERAL METHOD

The basic experimental task was the same in both of the first two experiments. On each trial the S was required to perform a compensatory tracking task while listening to and memorizing a list of eight letters. The tracking task required nullifying the movement of a 20 mm vertical line about a stationary vertical target line centered on a 5-inch CRT. The movement of the cursor was nullified by S using a joystick type control with positional dynamics. Each trial consisted of an uninterrupted period of 21 seconds of tracking. The first five seconds were regarded as warm-up and were not scored. The next eight seconds provided a baseline measure of tracking performance without the memory task, and the final eight seconds of tracking were accompanied by the presentation of the letter list. Following the last letter, the operator stopped tracking and wrote his recall of the eight letters under instructions to preserve the presentation order in recall

EXPERIMENT I: TIME-SHARING BETWEEN A MEMORY TASK AND A TRACKING TASK AS A FUNCTION OF SIGNAL COMPLEXITY (H. G. Shulman and D. Shinar)

The first experiment was done in order to explore the functional relationships obtained when a memory task and a tracking task are time-shared.

The basic experimental procedure described above was used. Independent variables were level of practice, and signal complexity in the tracking task. Each S served for eight sessions, the first two of which were used to familiarize S with the basic task requirements. In each of the next six sessions the S performed on an initial block of ten warm-up trials and then on two 15-trial blocks in which the experimental data were collected. Signal complexity was a within-S variable, with one of the 15-trial blocks in each session given to performance on a simple sinusoidal signal (.333 Hz) and the other to a complex signal consisting of the same basic sinusoid added to its second and third harmonics in phase.

The memory task consisted of the aural presentation (over headphones) of an eight-letter list at a rate of one letter per second. In Experiment I the S was simply asked to listen to these letters without responding, and to write his recall as soon as the tracking signal stopped. An incentive system was devised which encouraged the S to regard tracking as his primary task, and feedback for tracking performance was given on each trial. The Ss were 12 male students at The Ohio State University.

Results

Tracking performance

Absolute integrated error scores were obtained for each S on each trial, during the eight-second control period and during the eight seconds of tracking while listening to the memory task. Figure 1 shows performance in each of six sessions as a function of signal complexity for tracking alone (control) and while time sharing. Error scores represent averages taken over the eight-second observation interval. Each of the effects to be described below was found to be statistically significant by an analysis of variance.

First, time-shared performance was reliably worse than control performance, and this divided attention decrement was greater for the more complex signal. The effects of practice were most pronounced in the case of tracking with the complex signal, under both time-shared and single-task conditions. The time-sharing decrement was reduced by practice and this reduction was more apparent with the more complex signal.

Figure 2 shows the effects of time sharing on recall performance. The dependent variable was the number of letters correctly recalled in correct position within the list. Recall was in general worse when time-shared than under single-task conditions, and better when time-shared with the less complex tracking signal than with the more complex. Practice improved recall under both time-sharing conditions, but with the difficult tracking signal performance asymptoted at a level somewhat lower than single-task performance. A detailed analysis of the errors made in recall revealed no differential effects of tracking signal complexity on the incidence of various types of errors, although

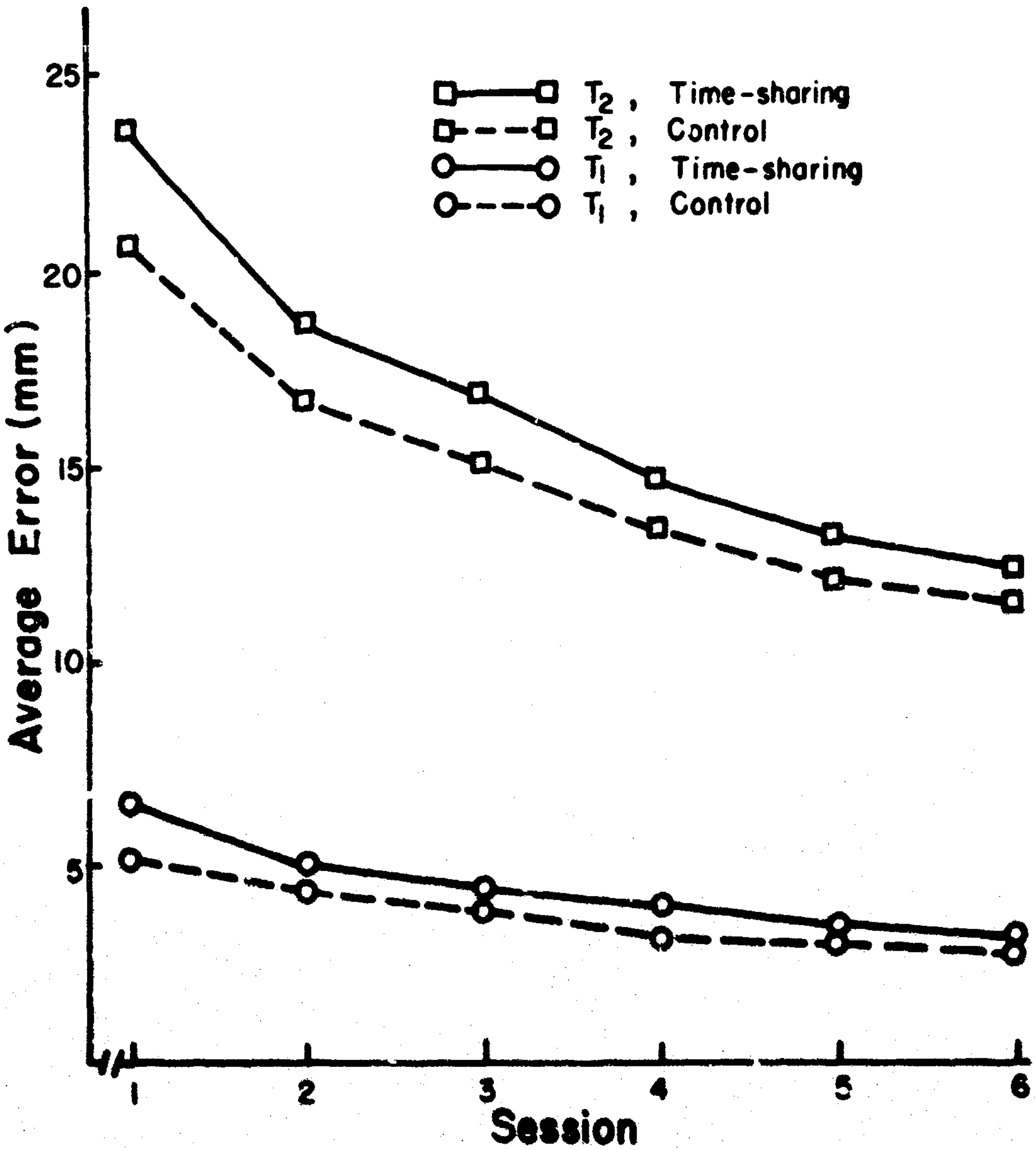

Figure 1 - Average error in tracking as a function of level of training, plotted separately for a simple signal (T_1) and a complex signal (T_2).

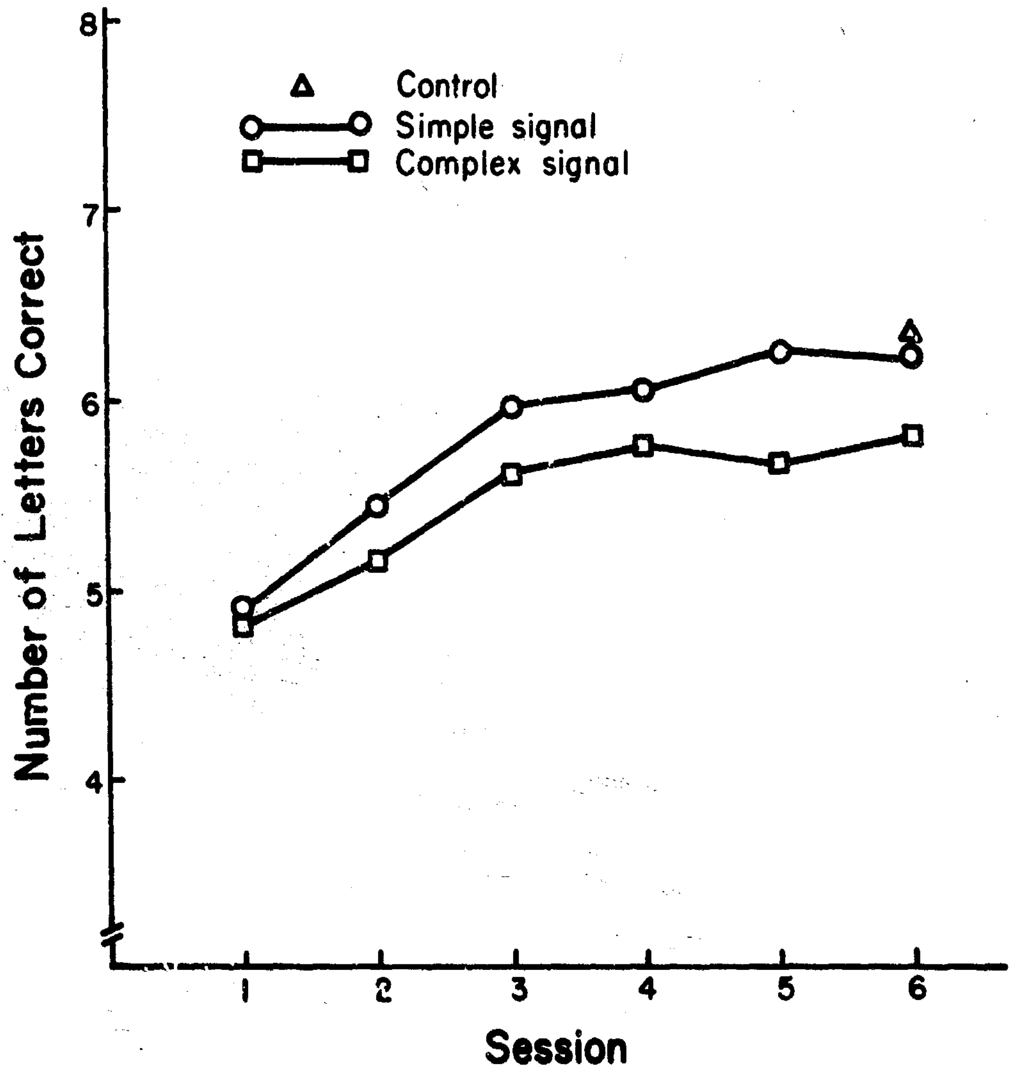

Figure 2 - Recall performance as a function of training level, plotted separately for the two levels of signal complexity used in the concurrent tracking task. Performance in a single task control condition is also shown.

the overall number of errors increased as signal complexity increased. The four types of errors noted and their relative frequencies were: omissions (.200), reversals of order (.272), acoustic intrusions (.165), and non-systematic intrusions (.363).

The most important feature of the recall data was an interaction between signal complexity and position in the letter list. The effects of signal complexity were more pronounced on the four items presented first and stored for the longest time before recall. Current theories of memory performance distinguish between long- and short-term memory (LTM and STM). In terms of this dichotomy a greater effect of signal complexity in the tracking task on the memory items held longest in store may be interpreted as reflecting the operation of a time-sharing effect on the process of transferring information from short-term memory to long-term memory.

The results of the initial experiment, then, quite clearly demonstrate time-sharing decrements in both tasks. Furthermore the manipulation of signal complexity in the tracking task led to time-sharing decrements in both tracking and memorizing which were greater the more complex the tracking task.

EXPERIMENT II: ACOUSTIC CONFUSABILITY AS A PARAMETER OF RECALL PERFORMANCE UNDER TIME-SHARED CONDITIONS (H. G. Shulman and D. Shinar)

The second experiment on simultaneous demand time sharing was similar in method to the first. Signal complexity on the tracking task was again manipulated as an independent variable in order to replicate Experiment I. In addition the difficult of the memory task was manipulated by varying the acoustic confusability of the letters used to construct the eight-letter lists. Confusability was a within-S variable with two levels, represented by a nonconfusable vocabulary (F,H,I,K,L, O,R,U,Y) and a confusable vocabulary (B,C,D,E,G,P,T,V,Z).

One important procedural difference between Experiments I and II was that in the second experiment Ss were required to shadow the letter lists as they were presented. A shadowing task is one in which S is required to vocalize the materials as soon as they are presented. It is a demanding task and was included in order to provide a means of determining whether misperceptions of the auditory materials occurred and if so whether such perceptual errors were related to the difficulty of the time-shared tracking task. Twelve Ss served in Experiment II.

Results

Tracking performance

The results of Experiment II replicated Experiment I. Time sharing degraded tracking, and the time-sharing decrement was greater

for the more complex signal. Practice again reduced the time-sharing decrement, and did so more effectively in the more difficult tracking task. The difficulty of the memory task was also reflected in tracking performance, with a more pronounced time-sharing effect evident when the memory materials were acoustically confusable. These data are shown in Fig. 3.

Shadowing performance

Table I shows the distribution of listening errors as revealed by errors in shadowing in the six conditions of the experiment. Shadowing errors were virtually absent with nonconfusable materials.

Table I. Distribution of Listening Errors*

Memory Condition	Tracking Condition		
	No Tracking	Simple Signal	Complex Signal
Acoustically Confusable	.284	.317	.396
Acoustically Nonconfusable	.004	.000	.000

*Cell entries are mean # of errors per 8-letter list. Each mean is based on 240 trials.

When the letters were confusable there was a noticeable time-sharing effect whose magnitude increased with signal complexity. These data indicate that the time-sharing decrement is partly due, then, to errors made in the initial encoding stage of information processing. This finding is explored in more detail in experiments reported later.

Recall performance

Recall data were corrected for shadowing errors by considering the recall of a letter correct if it matched the S's shadowing protocol, even if that protocol contained listening errors. The major results are shown in Fig. 4. There was a pronounced time-sharing effect which was greater for the more difficult (confusable) memory task. Thus the loading effect of tracking on memory performance increased with the difficulty of the memory task, just as the loading effect of memory task difficulty on tracking scores seems slightly greater the more difficult the tracking task.

As in Experiment I the effect of time sharing on memory was greater for the first presented letters in each list. These data are shown in Fig. 5. As in Experiment I, these are taken to reflect an

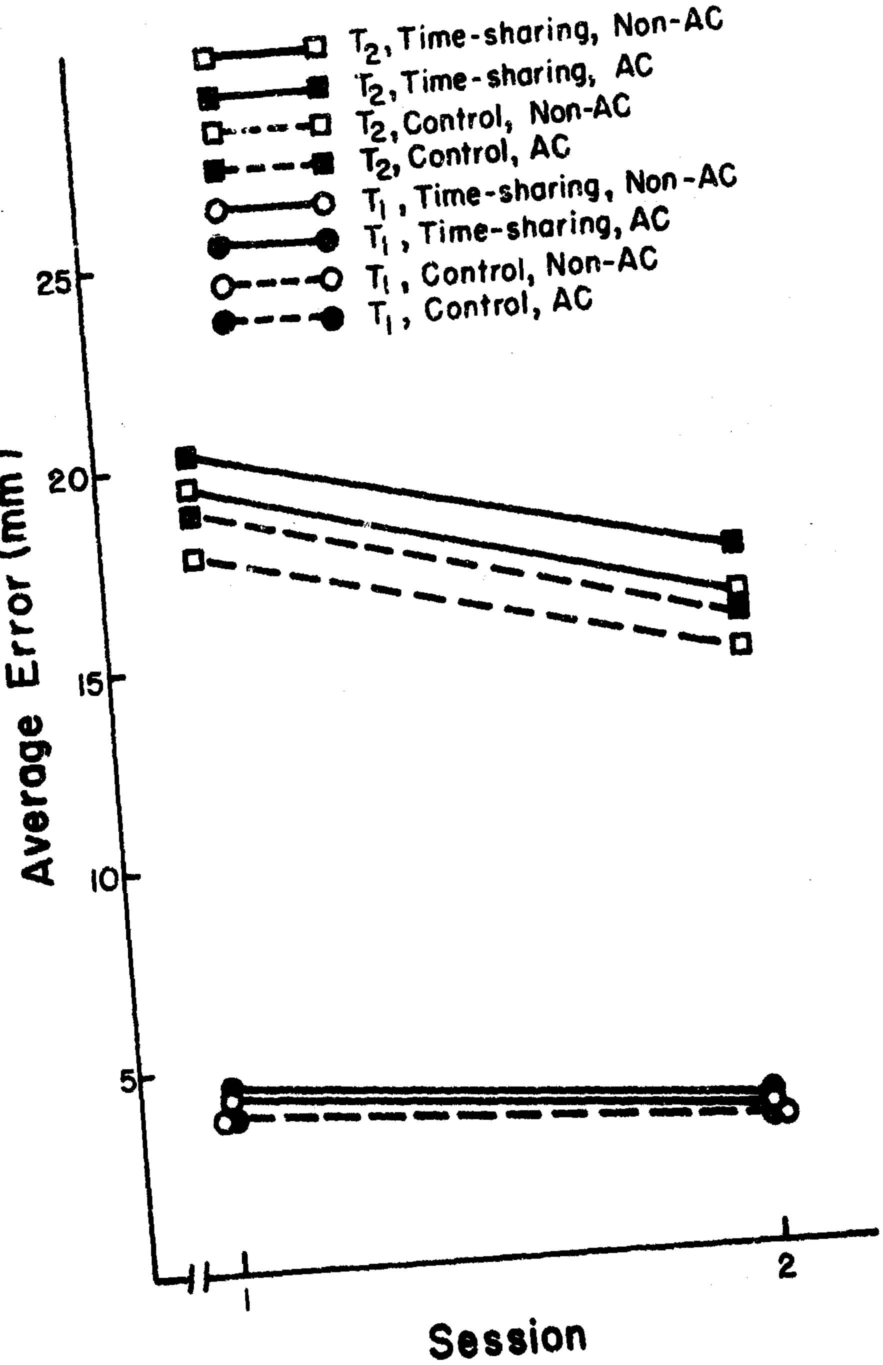

Figure 3 - Tracking performance as a function of experimental session and time sharing. Plotted separately for the nonacoustically confusable memory task and the confusable memory task. T_1 = simple signal, T_2 = complex signal.

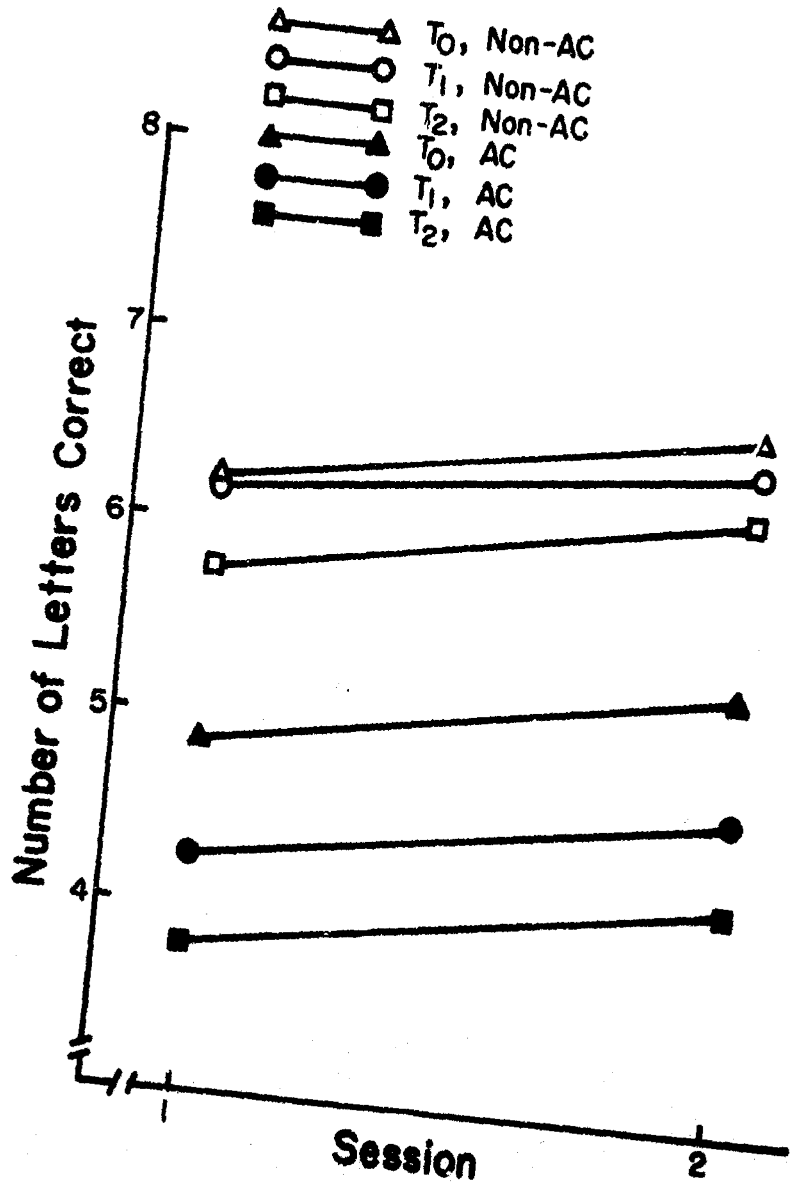

Figure 4 - Effects of time sharing on recall performance, plotted separately for acoustically confusable (AC) and non-confusable (non-AC) materials. T_0 = simple tracking signal, T_2 = complex tracking signal.

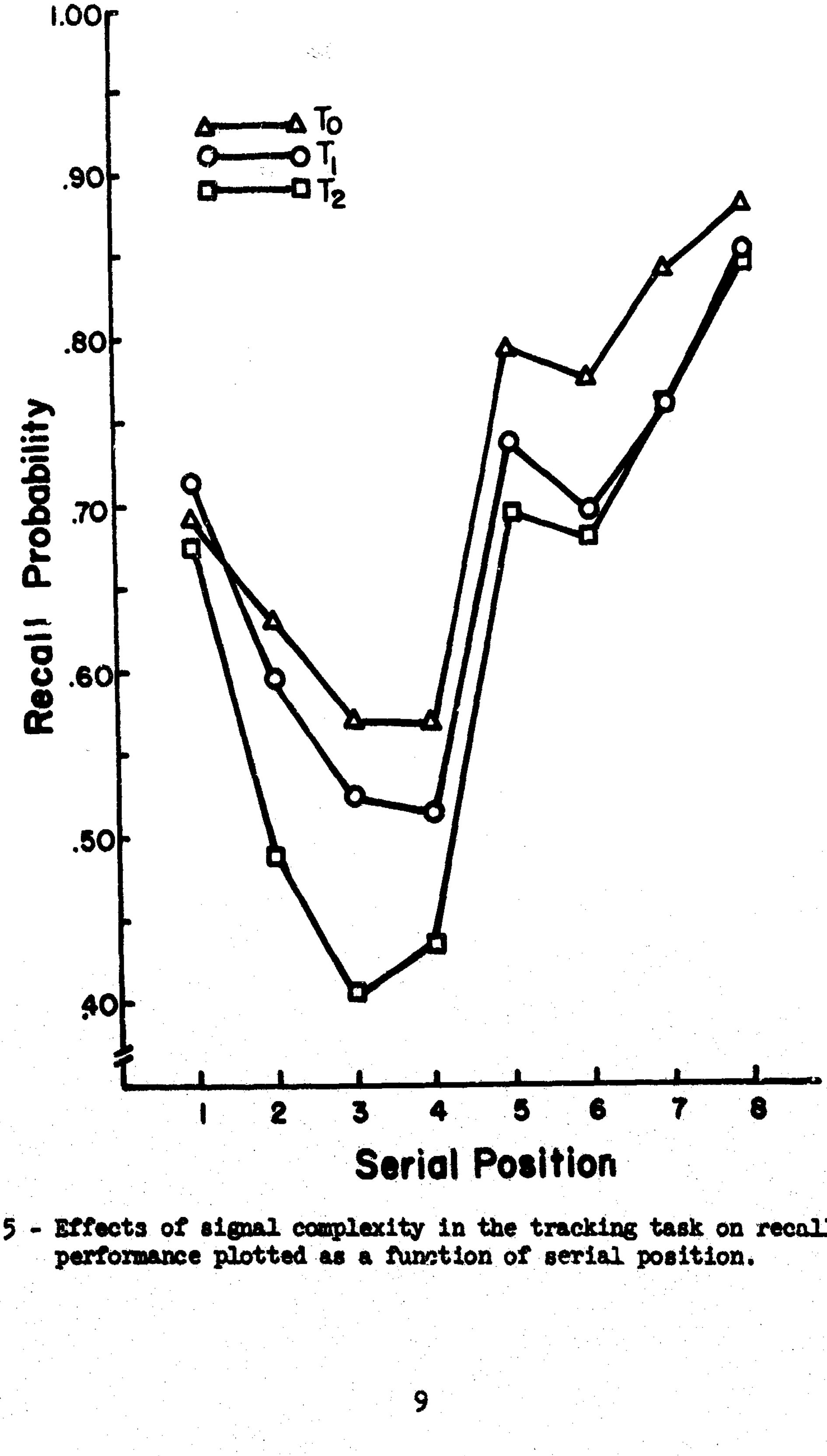

Figure 5 - Effects of signal complexity in the tracking task on recall performance plotted as a function of serial position.

influence of time sharing on the transfer of information from short- to long-term memory.

Summary

The first two experiments have demonstrated time-sharing effects on both tracking and memory. Furthermore the magnitude of the time-sharing decrement appears to be related to the level of difficulty of both tasks. Thus increased signal complexity caused a greater time-sharing decrement on both the tracking and memory tasks. The effects of practice are to reduce these decrements by an amount that is proportional to the initial decrement. Finally we have reported evidence that leads us to believe that the time-sharing effect observed on the memory task operates upon two types of information processing functions. First, the rate of transfer of information from short- to long-term memory is slowed by time sharing, and second the initial encoding of information appears to be impeded by time sharing.

EXPERIMENT III: ACOUSTIC VERSUS SEMANTIC CONFUSION IN A TIME-SHARED MEMORY TASK
(H. G. Shulman and D. Shinar)

The third experiment to be reported was an attempt to explore, in more depth, the finding that time sharing affects the encoding of information into memory. The simultaneous demand paradigm of Experiments I and II was used in order to study the manner in which tracking interacts with the encoding of acoustic and semantic information. Four types of memory lists were constructed. These were (1) lists containing acoustically confusable materials, (2) lists containing semantically confusable materials, (3) nonconfusable control lists matched to the acoustically confusable lists in terms of word length and frequency, and (4) nonconfusable lists matched to the semantically confusable lists in terms of word length and frequency. A reliable finding in studies of memory is that both acoustic and semantic confusability lead to recall errors. By studying the interaction of these two types of confusability with time sharing we hoped to discover whether the type of encoding (acoustic vs. semantic) used in the memory task might shift as a consequence of time sharing.

A total of 48 Ss participated in this experiment, 24 in each of two groups. The Ss in each group memorized six-word lists constructed from one of the confusable vocabularies and the appropriate control vocabulary, both while tracking and in the absence of tracking.

Results

Tracking

Average integrated error scores in arbitrary voltage units for the eight-second tracking periods both with and without time sharing are

shown in Table II.

Table II. Tracking Performance in Experiment III

Memory Task	Time Sharing	Tracking Alone
Acoustic Confusion	56.08	51.08
Acoustic Control	55.83	50.46
Semantic Confusion	54.62	51.25
Semantic Control	54.78	51.24

As in Experiments I and II there was a time-sharing decrement in tracking. However this decrement did not depend on variations in the memory task as had been our expectation.

Memory

Performance on the memory task failed to reflect in any sizable way our manipulation of semantic confusibility, although there were effects of the acoustic variable. Table III shows the recall results. Recall level in general was again reduced by the requirement

Table III. Percent of Words Recalled Correctly

Memory Task	Tracking	No Tracking
Acoustic Confusion	51.3	57.0
Acoustic Control	62.6	71.7
Semantic Confusion	61.1	70.5
Semantic Control	63.0	68.8

for time sharing. However the magnitude of this effect did not appear to be systematically related to the confusability of the memory materials, nor was the difference between confusable and nonconfusable materials affected by time sharing.

The results of Experiment III, then, while in agreement with those of the first two experiments, added little to our understanding of the effects of divided attention on encoding. We shall return to this issue in our report of a later experiment.

EXPERIMENT IV: DETERMINANTS OF THE DISTRIBUTION OF ATTENTION: EFFECTS OF CUEING PROBABILITY
(H. G. Shulman and R. P. Fisher)

In our fourth experiment we decided to study the ability of the operator to adjust his allocation of attention across two input sources in proportion to the importance of each source. This ability is of critical importance for optimizing performance under conditions of divided attention. Our initial attempt to study the ability to adjust capacity allocation made use of the divided attention paradigm used in Experiments I, II, and III. However we were unable to obtain reliable effects of variations in incentive for performance on the tracking and memory tasks. We believed this to be due to the heterogeneity of the two tasks and the fact that Ss in time-sharing tasks sometimes adopt the set to favor the task which is perceived to be most difficult. We felt it advisable to study capacity allocation in a setting which was free of such complicating influences, and devised a divided attention task of a simpler yet more analytical nature than the paradigm used in our first three experiments.

Method

The nature of the stimulus event on each trial was the same in all conditions of the experiment. On each trial S was simultaneously presented with a 50-msec light and tone and was then cued to report either the brightness of the light or the pitch of the tone. In the five experimental conditions the probabilities that each dimension would be cued after the stimulus presentation were varied, while the payoff for a correct report on either dimension was held constant. The five combinations of cueing probability were (1) 1.00 auditory - 0.00 visual, (2) .25 auditory - .75 visual, (3) .50 auditory - .50 visual, (4) .75 auditory - .25 visual, and (5) 0.00 auditory - 1.00 visual. Each of ten Ss participated in the experiment, experiencing each of the five cueing conditions once in five successive experimental sessions. A total of 192 trials in a single cueing condition were run in each 30-minute session. The compound stimuli consisted of the 16 possible combinations of 4 tones (880, 920, 960, and 1000 Hz) with 4 intensities of the light (7, 11, 16, and 24 ft. C.).

Results

Table IV shows transmitted information scores in the five conditions of the experiment, both separately for each dimension and totaled over the two dimensions. The main effects of dimension and cueing probability were both significant, as was the effect of cueing probability condition on total H_t. Performance on the pitch judgment was slightly superior to performance on the brightness judgment. In both dimensions performance increases with cueing probability, indicating that the S is able to exert some degree of rational control over the allocation of attention. The effect of conditions on total H_t

Table IV. Transmitted Information Scores in Bits for Each Cueing Probability

	Cueing Probability				
Dimension	1.0[a]/0.0[b]	.75[a]/.25[b]	.50[a]/.50[b]	.25[a]/.75[b]	0.0[a]/1.0[b]
Brightness	1.02	.98	.90	.77	--
Pitch	--	1.14	1.14	1.18	1.30
Total	2.32[c]	2.12	2.04	1.95	

[a]cueing probability for brightness

[b]cueing probability for pitch

[c]total for conditions 1.0[a]/0.0[b] and 0.0[a]/1.0[b]

reflects the fact that as increasing weight is assigned the visual dimension, the total resolving power of the S increases. In other words, more is gained by emphasizing the visual than the auditory stimulus. This may be due either to a modality preference or to a bias towards the more difficult of the two dimensions.

EXPERIMENT V: DETERMINANTS OF THE DISTRIBUTION OF ATTENTION: EFFECTS OF PAYOFF VALUE (H. G. Shulman and R. P. Fisher)

The results of Experiment IV demonstrated that the S can readjust the allocation of processing capacity across two input channels in proportion to the probability that each channel will carry information relevant to the response required on each trial. Since the payoff for each correct response in Experiment IV was held constant over dimensions and trials, the manipulation of cueing probability was also a manipulation of expected value. In Experiment V cueing probability was held constant while payoff varied, in order to converge upon the hypothesis that it is expected value which provides the criterion for capacity allocation.

Method

The experimental procedure was almost identical with the procedure used in Experiment IV. In all five experimental conditions the cueing probabilities for audition and vision were equal at p = .50 per dimension. The five conditions differed in the distribution of the payoff values for correct responses in the two modalities. In one condition the visual dimension was assigned a payoff value of .6¢ per trial while 0¢ per trial was paid for each correct judgment of pitch. In a second condition these payoffs were reversed. The third condition paid equal amounts (.3¢ per correct response) for correct judgments of pitch and

brightness, and in the fourth and fifth conditions values of .45¢ and .15¢ were assigned to the two dimensions, the assignments being reversed in the two conditions.

The same 10 Ss who had served in Experiment IV returned to the laboratory for the five sessions of Experiment V. A total of 192 trials per session were run, and each session was given to a single experimental condition.

Results

Table V presents transmitted information scores for Experiment V. As in the previous experiment the main effect of modality was significant, reflecting superior performance on the pitch judgment. The effect of payoff value was also significant, indicating that for each modality the operator was able to adjust his allocation of processing capacity according to the relative amount to be gained by attending to each information source. Taken along with the results of the previous experiment these data indicate that expected value is one means by which the operator is capable of allocating attentional capacity across multiple input sources.

Table V. Transmitted Information Scores in Bits for Each Payoff Value

	Payoff Value				
Dimension	.60[a]/0[b]	.45[a]/.15[b]	.30[a]/.30[b]	.15[a]/.45[b]	0[a]/.60[b]
Brightness	1.02	1.12	1.00	.91	.69
Pitch	.98	1.15	1.16	1.31	1.26
Total	2.00	2.27	2.16	2.22	1.95

[a]cueing probability for brightness
[b]cueing probability for pitch

The results of Experiments IV and V are summarized in Fig. 6, where performance on the two types of judgment is shown as a function of expected value. (The dependent variable in Fig. 6 is proportion correct rather than transmitted information. In the present data these two dependent variables were related to each other monotonically so that for each analysis reported the pattern of results remains unchanged when one compares H_t scores and proportion correct). In the literature on divided attention, very little research on the question of determinants of capacity allocation has been reported. We feel that the present research represents an important demonstration of the fact that Ss can be brought to exert rational control over the distribution of attention in a time-sharing paradigm. This demonstration is rich with implications

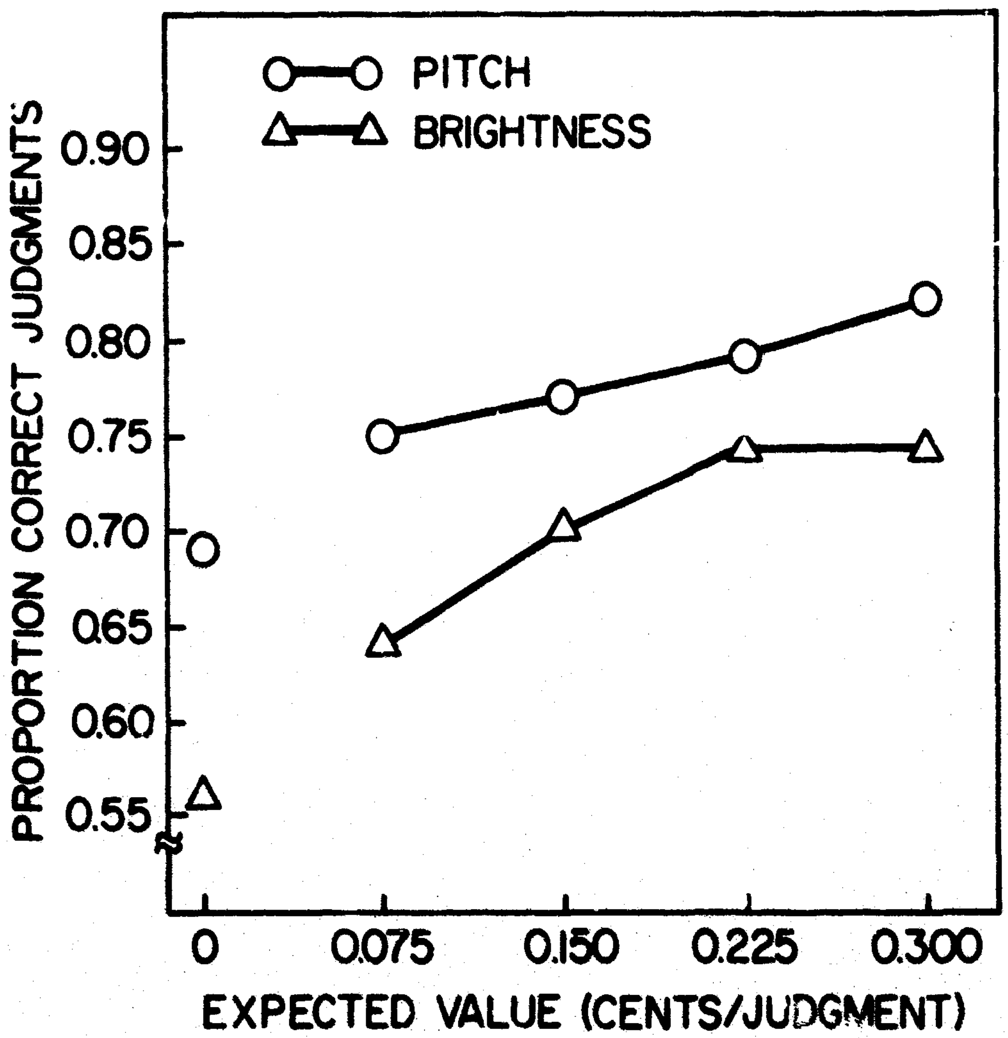

Figure 6 - The results of Exp. IV and V combined and plotted as a function of the expected value of each correct response.

for future research into the parameters of efficiency in capacity allocation, and will eventually have implications for system design.

TIME SHARING IN THE SEQUENTIAL DEMAND PARADIGM

Our initial experiments on sequential demand time sharing focused on three objectives. The first was simply to determine whether a time-sharing decrement could be observed in the sequential demand situation. The second, predicated on a positive answer to the first, was to test the hypothesis (mentioned earlier) that one locus of the time-sharing decrement is the encoding process. The third was to investigate the boundary conditions of the time-sharing effect. Our research in the simultaneous demand paradigm could not provide an answer to the question of whether the time-sharing decrement occurs only when two tasks compete with each other for the use of a specific processing mechanism (such as encoding), or whether the decrement will occur even when each of the two tasks loads distinct processing functions such as encoding and information storage. The simultaneous demand paradigm is unsuitable for testing this hypothesis because by definition this paradigm involves the simultaneous presentation of stimuli and elicitation of responses in the two tasks, hence it is never possible to study time sharing under conditions where the two tasks have minimal overlap in terms of the demands made on specific processing functions.

EXPERIMENT VI: PERCEPTUAL DEFICIT DUE TO DIVISION OF ATTENTION BETWEEN MEMORY AND PERCEPTION (H. G. Shulman and Seth N. Greenberg)

The sixth experiment concerned the effects of information storage on performance in a perceptual task. An STM task and a detection task were presented successively in order to eliminate overlap in the perceptual demands made by the two tasks. Divided attention was therefore required in the sense that <u>after</u> encoding information into memory, a perceptual task had to be performed and the performance of this perceptual task overlapped with the covert storage of information in STM This paradigm requires sequential demand time sharing since the stimulus information for the perceptual task occurred immediately <u>after</u> the presentation of the memory materials. The major independent variables were (1) the duration of the stimulus exposure in the perceptual task, and (2) the amount of information presented for storage in STM.

Method

Two types of trials were used, representing the experimental conditions and a control condition. On Experimental trials the presentation of a consonant list preceded the presentation of a visual display consisting of a single numeral. The consonant list was presented aurally

at a 1-second rate. One second after the last consonant was presented, and prior to recall of the consonant list, a brief visual display consisting of one of the numerals 5, 6, or 8 was presented. The S immediately recorded his forced-choice judgment regarding the number in the display and then wrote his recall of the consonant list. The independent variables were the length of the consonant list (3, 5, 7, or 10 letters) and the exposure duration of the visual presentation.

On the Control trials, performance was required on both the perceptual and memory tasks, but performance on the perceptual task preceded the presentation and recall of the consonant list by 2 seconds. The memory task on all Control trials consisted of the presentation and recall of a 10-consonant list.

Design

Each of the 16 Ss participated in five 50-minute sessions on consecutive days. The first two sessions were given to the determination of 60% and 90% duration thresholds using a short-cut psychophysical procedure, and to practice at dual-task performance. The next three sessions each consisted of 64 Experimental and 16 Control trials. Each S served in every condition of the experiment, and each condition was used for eight trials in each session. There were ten conditions representing the factorial combination of memory load (10-letter Control plus 3-, 5-, 7-, and 10-letter Experimental conditions) with exposure duration (60% and 90% duration thresholds).

Results

Performance on the perceptual task is shown in Fig. 7 as a function of list length in the memory task. The effects of both list length and exposure duration were significant, while their interaction was not. These results demonstrate a reliable divided-attention decrement since performance in the control conditions (list length of zero) was superior to performance when information storage was required. Furthermore the magnitude of the time-sharing decrement increased with the load on memory up to seven letters, which represents the approximate limit of STM capacity. Further discussion of these data will be postponed until the results of Experiments VII and VIII have been considered.

EXPERIMENT VII: TIME SHARING BETWEEN PERCEPTION AND MEMORY IN A CHOICE REACTION TIME PARADIGM

(H. G. Shulman and S. N. Greenberg)

Performance on the perceptual task in Experiment VI was a decreasing function of memory task difficulty under conditions designed to minimize specific overlap in the information-processing demands of the two tasks. However it might be argued that the perceptual recognition task used in Experiment I involved the storage of the three numerals 5, 6, and 8 in STM in preparation for comparison with the test stimulus.

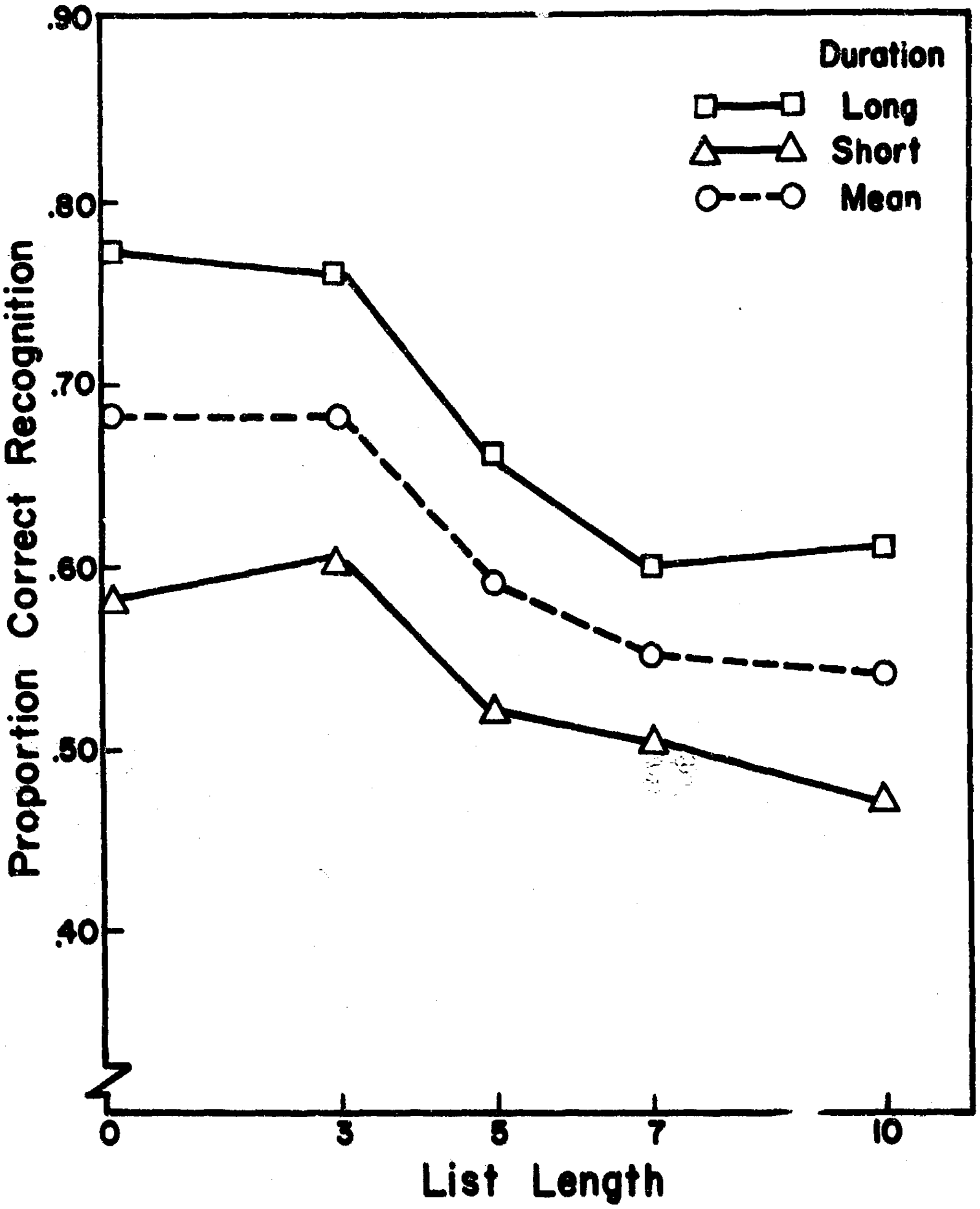

Figure 7 - Accuracy in perceptual recognition as a function of memory load in the time-shared task.

If this were true, then the time-sharing decrement observed in Experiment VI might reflect conflicting demands made on a single processing function (memory) rather than conflict between two normally independent processes such as perceptual encoding and memory. In Experiment VII a perceptual task was chosen to minimize this possibility. Experiment VII also differed from Experiment VI in that accuracy on the perceptual task was maximized in Experiment VII by using a long exposure duration, and choice RT was used as the performance measure, in an effort to determine whether the time-sharing decrement would affect the speed of processing under conditions of highly accurate performance.

Method

For both Experimental and Control trials, the basic procedure in Experiment II was the same as in Experiment I. The major change was that S was required to report his perceptual judgment by depressing a response button instead of circling one of three alternatives. The duration of the visual display was 5 seconds, and Ss were given 12 seconds in which to write their recall of the consonant list. The apparatus used was described in Experiment I.

Design

The independent variable in Experiment II was list length. In four experimental conditions, consonant lists of lengths two, four, six, and eight were used. Control trials required performance on the perceptual task only. Each S served for a single session consisting of an initial 10 practice trials and 15 trials in each Experimental condition and the Control condition. The 15 trials in each Experimental condition were blocked, and the order of occurrence of Experimental conditions was determined by a balanced Latin-square design requiring four Ss. The Control trials were administered in three blocks of five trials occurring before the first block of experimental trials, after the last, and between the second and third blocks of 15 Experimental trials. The consonant lists were constructed from the letters J, Z, H, N, L, X, F, and G according to the same constraints used in Experiment VI.

The perceptual task involved comparative judgment of line length. On each trial the visual display consisted of two vertical lines of unequal length drawn in black ink on a white background. These lines were drawn from an imaginary common base to heights of either 5.08 or 5.59 cm, and they were separated by 2.54 cm. The S's task was to report whether the left or right line appeared longer by depressing one of two response buttons on which he rested his index fingers. Depression of the left response button signified that the line on the left was judged longer, and depression of the right button signified the opposite. For a given S, in each block of 15 trials the longer line was on one side of the display eight times and on the other side seven times. Each response was correct exactly 50% of the time in each condition over pairs of Ss, and for a given S over successive 15-trial blocks.

Subjects

Thirty-two Ohio State University undergraduates, 16 males and 16 females, served as Ss in fulfillment of a course requirement.

Results

The basic data in this experiment were the median RT's for the comparative judgments of each S in each condition. Thirty-two scores were obtained in each condition, and each score was the median of 15 RTs. Figure 8 shows the mean of these median RTs as a function of memory load. The control condition is plotted as a list length of zero. An analysis of variance revealed a significant effect of memory load on RT. Error rates in the five conditions of the experiment averaged .29% and ranged from errorless performance in the four-letter condition to .63% in the two-letter condition.

The results of Experiment VII, then, confirm the findings of Experiment VI and permit generalization of the time-sharing effect to measures of speed taken under conditions of high accuracy. The implication of the two experiments taken together is that the time-sharing decrement is localized in stimulus encoding. This effect occurs, however, primarily when moderately heavy loads are placed on STM, since there is no evidence in the data of a decrement in perceptual performance when the load on STM is less than five items and their associated order information.

EXPERIMENT VIII: INTERTASK DELAY AS A PARAMETER OF THE TIME-SHARING DECREMENT IN A SEQUENTIAL DEMAND PARADIGM

(H. G. Shulman, S. N. Greenberg, and J. Martin)

The eighth experiment to be reported was an investigation of the effects of delay in the onset of the perceptual task relative to termination of the presentation of the memory materials in the paradigm described in Experiment VII. During an unfilled time interval following the memory materials the S should be able to consolidate his memory for these materials by transferring them to long-term memory. The experimental question was whether the perceptual time-sharing decrement would be reduced by this transfer. Such a result would imply that loading STM causes a time-sharing decrement, while loading LTM does not.

Method

The method and procedure were almost identical to the previous experiment (Experiment VII). The only differences were that memory loads of 3, 6 and 9 letters were studied, and a new variable, intertask delay, was added to the design. Thus the onset of the visual display followed the auditory presentation of the last letter to be memorized by either 2, 5, or 8 seconds.

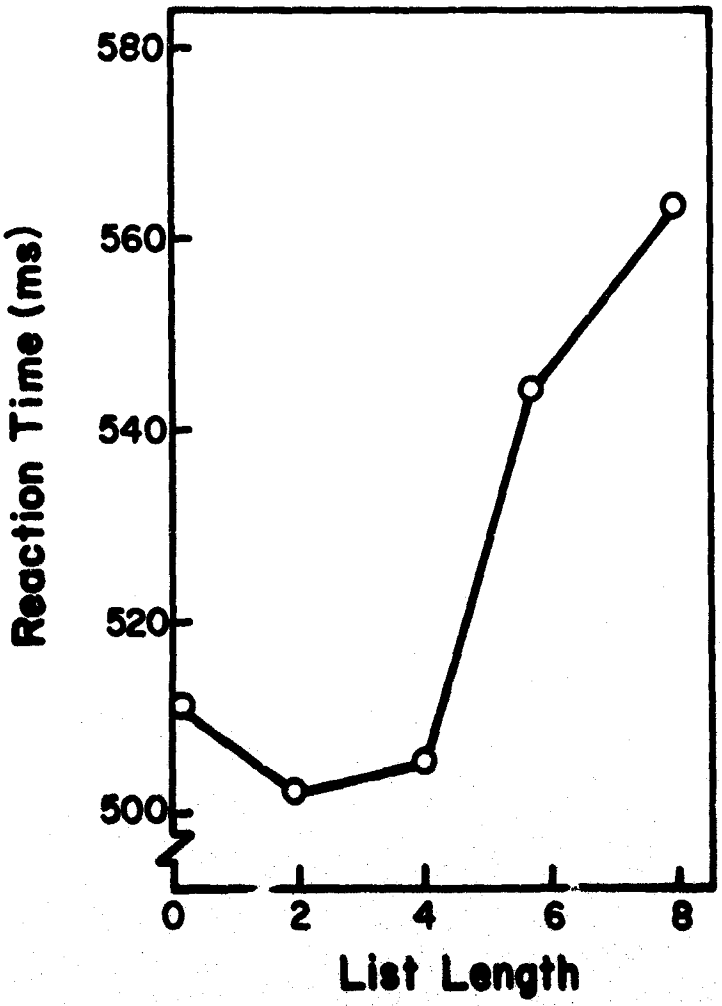

Figure 8 - Mean RT for perceptual recognition as a function of memory load in the time-shared task.

Results

Table VI shows the effects of memory load and intertask delay on RT in the perceptual task. The magnitude of the time-sharing deficit is dependent on both factors and their interaction. Thus for each delay, RT increases with memory load, and for each memory load RT decreases as delay increases. Furthermore, there is a greater effect

Table VI. Mean RT(in msec) for Perceptual Judgment

Delay (Sec.)	Memory Load 3	6	9
2	439	462	474
5	435	444	465
8	435	439	450

of delay at the two larger memory loads than at the smallest. It is assumed that the functional STM load decreases as the delay of the perceptual task increases, because information is transferred from STM to LTM. The time-sharing decrement, then, apparently reflects competition for processing capacity between the processes of maintaining information in STM and encoding perceptual information.

Our next series of experiments on sequential demand time sharing focused on a paradigm in which the load placed on memory remains below the critical level of 5-7 items indicated in Experiments VI, VII, and VIII, but which nonetheless reveals a time-sharing decrement. The critical feature of this experiment is that the time interval between successive stimulus events is short, generally ranging from 10 to 1000 msec. Thus speed stress is created and divided attention is required either in the form of rapid reallocation of processing capacity from one stimulus to the next or in the form of the need to encode the present stimulus while still selecting or executing a response to the prior event. The general method is to present the S with a series of trials separated by about 8 seconds. Each trial consists of the presentation of two stimuli in close temporal proximity, with a speeded response required to each stimulus. The time-sharing decrement in this paradigm was first noted by Craik (1947) and has been the subject of a large number of experiments in the past two decades. The basic result to be explained is that the closer the temporal proximity of the two stimuli the longer is the RT to each, with the greatest delay usually occurring to the second stimulus. This result is often referred to as the Psychological Refractory Period (PRP) effect, and represents a form of sequential demand time-sharing decrement. The purpose of our research in this paradigm was to localize this decrement with respect to processing functions such as stimulus encoding, response selection, or central information processing.

EXPERIMENT IX: THE LOCUS OF THE PSYCHOLOGICAL REFRACTORY PERIOD EFFECT
(H. G. Shulman and J. Hayes)

Recent research on reaction time has frequently made use of a task first used by Sternberg (1966) which is capable of providing the analytic power necessary to localize various effects with respect to the processing function mentioned above. In this procedure the S is given a set of 1, 2, or 4 items (numerals, letters, or words) to be held in memory over a block of trials. These items are called the target set, and the manipulation of target set size (1, 2, or 4 items generally) is a basic feature of experiments using this procedure. On each of a series of test trials following memorization of the target set, a single test item is presented and the S is required to make one of two responses: "yes" if the test stimulus is a member of the current target set, or "no" if it is not. Typically one finds a monotonic (either linear or logarithmic) relationship between target set size and RT.* The analytic power of this procedure derives from the interpretation of the intercept and slope constant of the function relating RT to either target set size or log target set size. The intercept of this function includes the times for all cognitive processes whose operation is independent of target set size. The time taken to encode the test stimulus and to select the response (either "yes" or "no"), once the test stimulus has been encoded, thus contribute to the intercept. The total amount of time taken to compare the test stimulus to the members of the target set varies with the number of items in the target set, and these differences in total comparison time across set sizes determine the slope of the RT function. In fact, the slope of the RT function is interpretable as the amount of time taken per comparison in memory.

By determining whether an independent variable affects the slope or the intercept of the RT function it is possible to localize that variable's effect. In the present research our initial question was whether the sequential demand time-sharing decrement (or PRP effect) could be localized as either a slope or an intercept effect.

Method

The basic experimental objective was to study speed stress and the sequential demand situation using the Psychological Refractory Period experiment. In this experiment two reaction time tasks are defined for the subject and then on each trial two stimuli, one from each task, are presented and speeded responses to each required. In the present instance the first task was a red-green discrimination, and the second a character classification task as used by Sternberg. The sequence of events on each trial was as follows: (1) The target set for the character classification task was presented for memorization. This consisted

*The choice of scale depends for the most part on the details of the underlying information processing model assumed. In the present research we could plot the data either way without being forced to alter our conclusions about the time-sharing decrement.

of either 1, 2, or 4 numerals. (2) Two seconds after the presentation of the target set either a red or a green light appeared on the S's display panel. The S was instructed to depress one button if red appeared, another for green. (3) Either 100, 200, 400, 500, 600, or 900 msec after the color stimulus appeared, a numeral appeared next to the color patch on the display panel. This numeral was to be classified with respect to membership in the target set, and a vocal response, either "yes" or "no" emitted. Each trial then resulted in two pieces of data, RT_1, the reaction time to the first (color) stimulus, and RT_2, the reaction time for character classification. Each of 18 Ss served in the 18 conditions of the experiment defined by the factorial combination of 3 target set sizes (s = 1, 2, or 4) with 6 inter-stimulus intervals (ISI). The Ss were male volunteers from the Ohio State student population. Each S served in 8 one-half hour sessions, the first two of which were practice, while in each of the final 6 sessions performance was measured at a single ISI for all three target set sizes. The order of administration of ISI's over sessions and of target set sizes within sessions were each counterbalanced over S's.

Results

Figure 9 shows the linear function relating RT_2 to memory load separately for each ISI. The main effects of both memory load and ISI are significant, while the interaction of these two variables produced an F-value less than one. Thus ISI did not affect the slope of the RT function; instead it produced an intercept effect. The nature of this intercept effect is revealed in Fig. 10 where the intercept value of each of the RT functions shown in Fig. 9 is plotted against ISI. The time-sharing decrement appears as a progressive increase in the intercept value as the ISI becomes shorter. The maximum size of this effect is -268 msec, relative to RT at the longest ISI where asymptotic performance was achieved. This represents a decrease in speed of roughly 30%, a very sizeable time-sharing decrement. The effect of ISI on RT_1 is also shown in Fig. 10. This effect was also statistically reliable but much smaller than the RT_2 effect, the largest difference in the RT_1 data being 34 msec.

The results of Experiment IX, then, indicate that the sequential demand decrement is localized in processes contributing to the intercept of the functions shown in Fig. 8. By the logic described earlier, the two processes which might make a contribution to a change in the intercept value are stimulus encoding and response selection.

A comment on the relationship between this experiment and Experiments VI, VII, and VIII is relevant at this point. The results of those three experiments indicated that when short-term memory is loaded with five or more items and associated order information, the speed or accuracy of stimulus encoding is retarded. One might expect, then, that the PRP effect obtained in the present experiment must also be an encoding as opposed to a response selection effect. However, in the

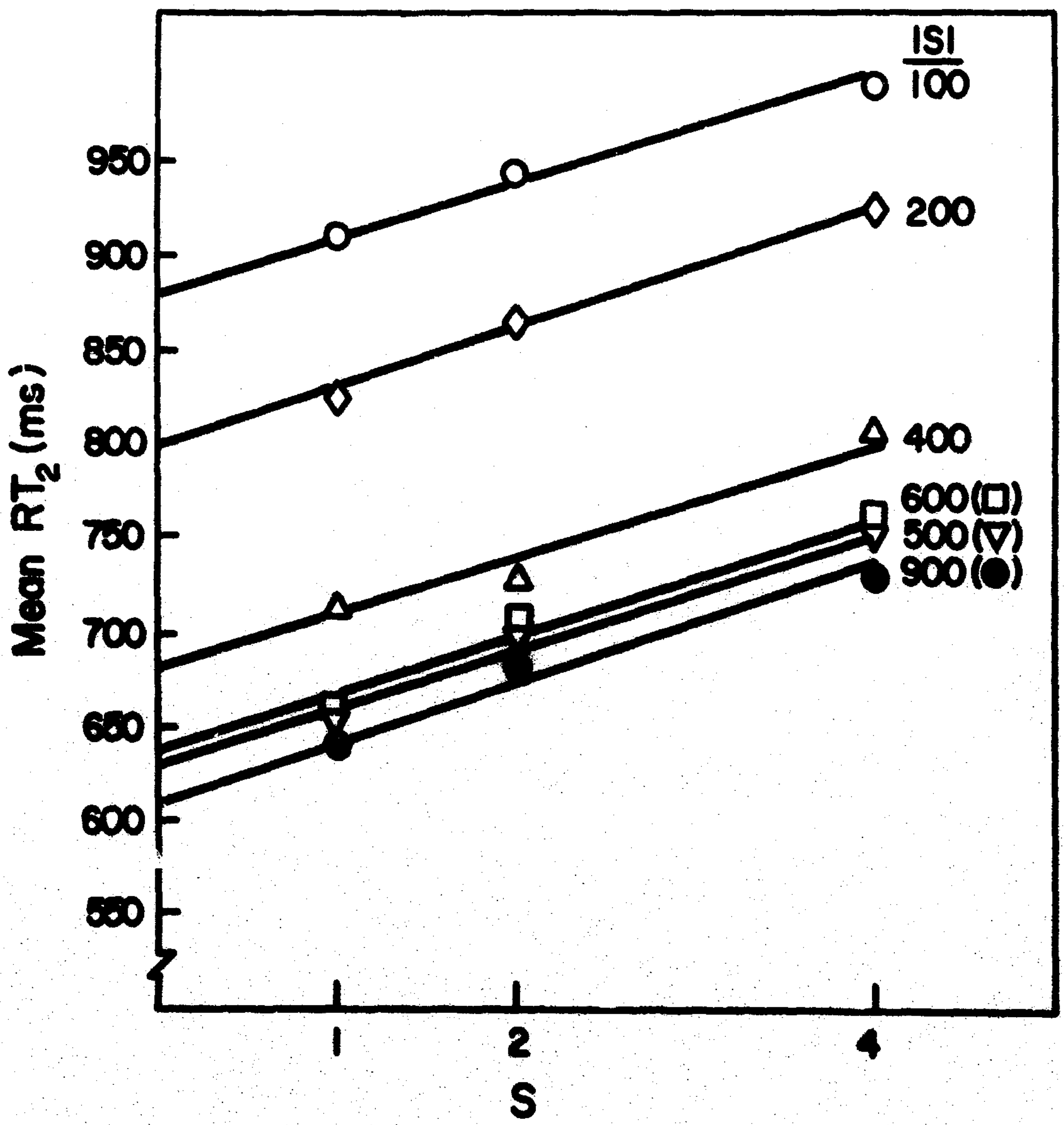

Figure 9 - Reaction time in the character classification task plotted as a function of target set size (S) in each ISI condition.

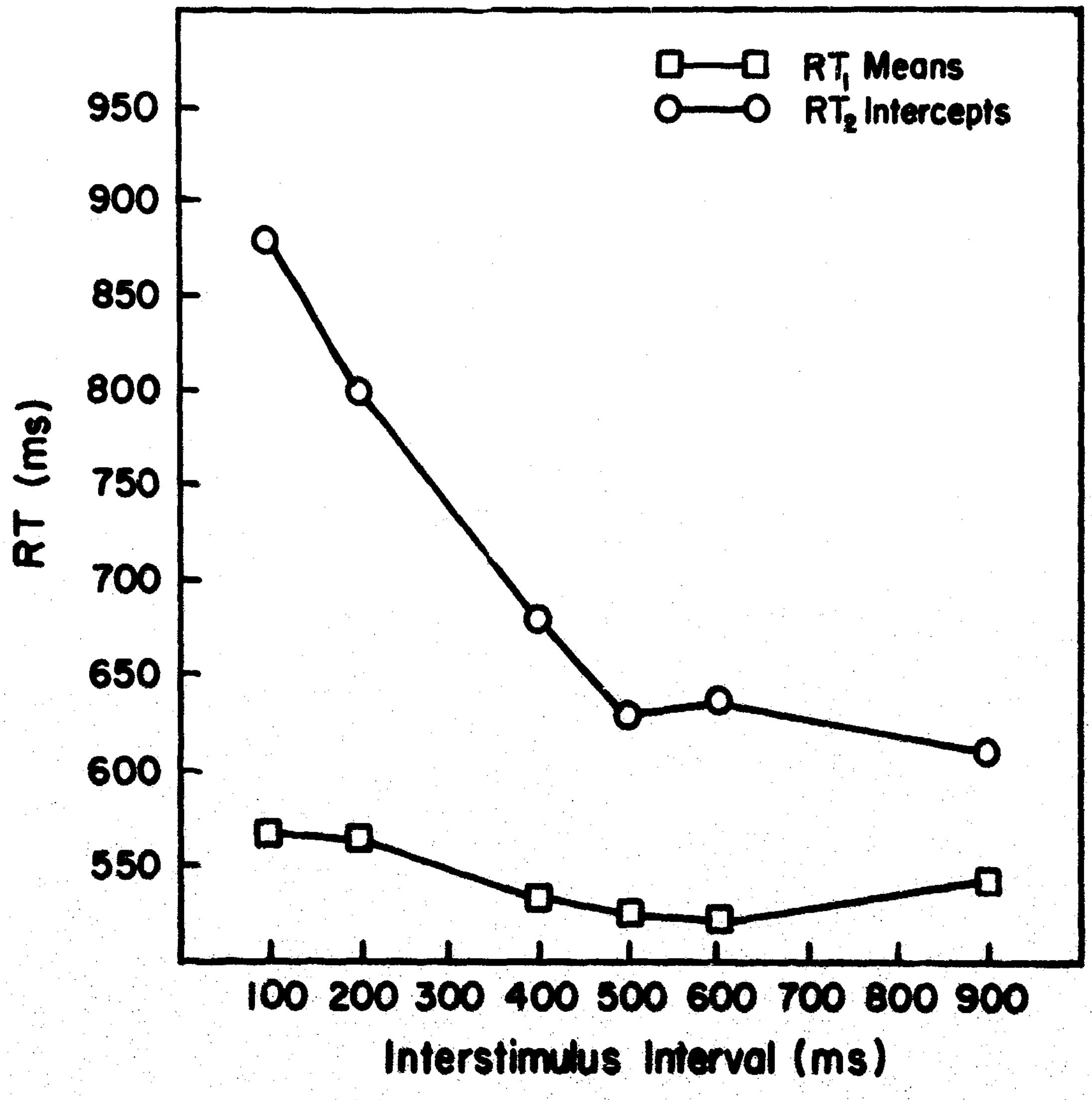

Figure 10 - Intercept values of the functions in Figure 9 are plotted against ISI in the top function. The bottom function shows RT in the color discrimination task presented first on each trial, as a function of ISI.

present experiment the memory loads used never exceeded four items with retention of order information not required, and the RT for the color discrimination task (RT_1) was not affected by this memory load. In fact, mean RTs for the color discrimination task were 548, 546, and 549 msec for target set sizes of 1, 2, and 4, respectively. A further difference between Experiments VI - VIII and the present experiment was that the time intervals between tasks 1 and 2 ranged from 2 to 8 seconds in the earlier experiments and from .1 to .9 seconds in the present case. Taken together these facts led us to refrain from concluding that the PRP effect represents another instance of a time-sharing effect on stimulus encoding. In fact, other research reported in the literature biased us toward aiming our next experiments at the response selection stage as the most likely source of the PRP decrement. In order to investigate response selection in the sequential demand paradigm used in Experiment IX, it was first necessary to perform an experiment designed to identify a variable which we could use to load the response selection process. This experiment will be reported next. Having isolated such a variable we then returned to the paradigm used in Experiment IX, adding the response selection variable, in an attempt to discover whether the effects of that variable would interact with the effects of ISI. This result would permit the conclusion that the PRP effect is localized in response selection.

EXPERIMENT X: S-R COMPATIBILITY, R-R DISCRIMINABILITY AND RESPONSE SELECTION IN CHOICE REACTION TIME
(H. G. Shulman and A. M. McConkie)

Kornblum (1965) reported that RT for a particular response member (the right middle finger) varied significantly as a function of whether the right or left index finger was used as the other response member in a two-choice RT task. We viewed this as a manipulation of response discriminability and decided to replicate and extend Kornblum's finding for the purpose of validating this manipulation of response discriminability as a means of influencing response selection.

Method

Two levels of S-R compatibility and two of R-R discriminability were factorially combined to define four between S conditions. The experimental task was a two-choice RT experiment requiring button press responses to visual stimuli. Eight Ss were assigned to each of the four treatment groups on the basis of their performance on a simple RT pretest, and each performed 600 choice RT trials in a single session.

The two stimuli consisted of the letter X presented either at the extreme left or right of a visual display, a distance measuring 8° of visual angle. R-R discriminability was varied by manipulating response ensembles: in one R-R condition the two responses were made with the left and right index fingers, and in the other responses were made with the right index and middle fingers. S-R compatibility was varied by

using either a direct or crossed assignment of stimulus positions (left or right) to response members (leftmost or rightmost of whatever two fingers a S was using).

Results

Figure 11 shows mean RTs for each block of 50 trials in each of the four conditions of the experiment, for responses made with the right index finger only. The main effects of S-R compatibility (47 msec) and R-R discriminability (47 msec) are equal, significant, and almost perfectly additive. This last fact indicates that the codes used to represent S-R and R-R relationships are properly regarded as independent constructs. More important for the present purpose is the finding that the response discriminability variable exerts a stable and sizeable effect on RT. Our next experiment took advantage of this fact in order to determine whether the sequential demand decrement observed in Experiment IX might be localized in the response selection process.

EXPERIMENT XI: RESPONSE SELECTION PROCESSES IN THE PSYCHOLOGICAL REFRACTORY PERIOD

(H. G. Shulman, J. Hayes, and A. M. McConkie)

Method

The experimental method and design were basically the same as in Experimental IX. Task 1 on each trial was a red-green discrimination; Task 2 was a numeral classification requiring a "yes" or "no" response. In the present experiment the red-green discrimination required a vocal response (red = "one", green = "two") and the character classification a button press response. Independent variables were (1) memory set size in the numeral classification task (s = 1, 2, or 4), (2) ISI (task 1 - task 2) interval (ISI = 100, 300, 500, or 900 msec), and (3) response discriminability in the numeral classification task, manipulated by requiring that "yes" and "no" responses be made with either two fingers on the same hand or one finger of each hand.

Results

Figure 12 shows the major results of Experiment XI, plotted as a function of memory set size. Reaction times made with response ensembles selected from a single hand were slower than those made in the two hand conditions by an average of 66 msec. The sequential demand decrement is again present, the difference between mean RT at ISI = 100 and ISI = 900 being 257 msec, which is similar to the decrement observed in Experiment IX (268 msec). Neither the response discriminability effect nor the ISI effect interacted with target set size, as indicated by the lack of any systematic slope differences in the functions of Fig. 12. Since both ISI effects (the time-sharing effects) and response discriminability effects are localized in the intercepts

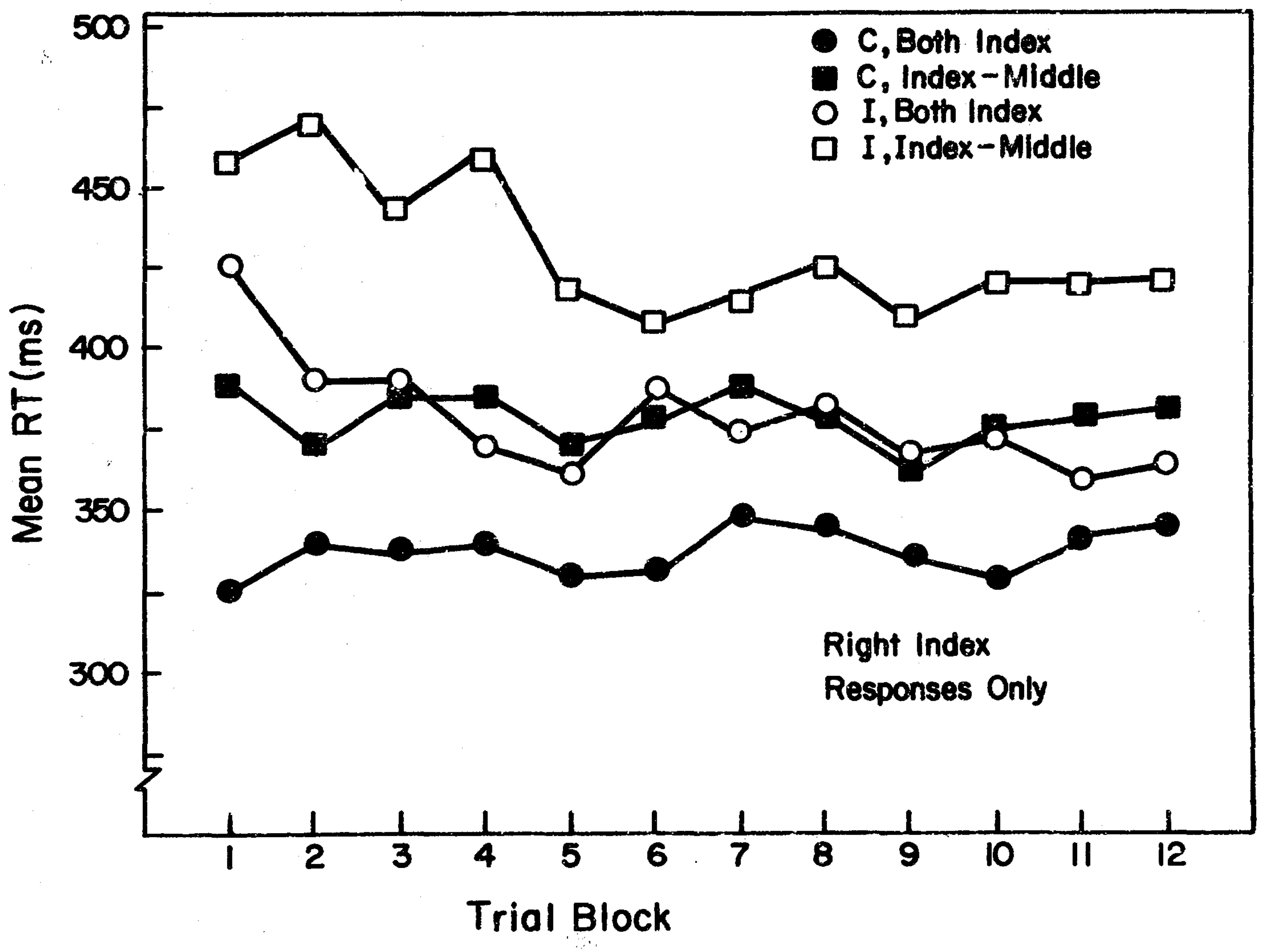

Figure 11 - Mean reaction time as a function of practice, plotted separately for each combination of S-R compatibility and response discriminability.

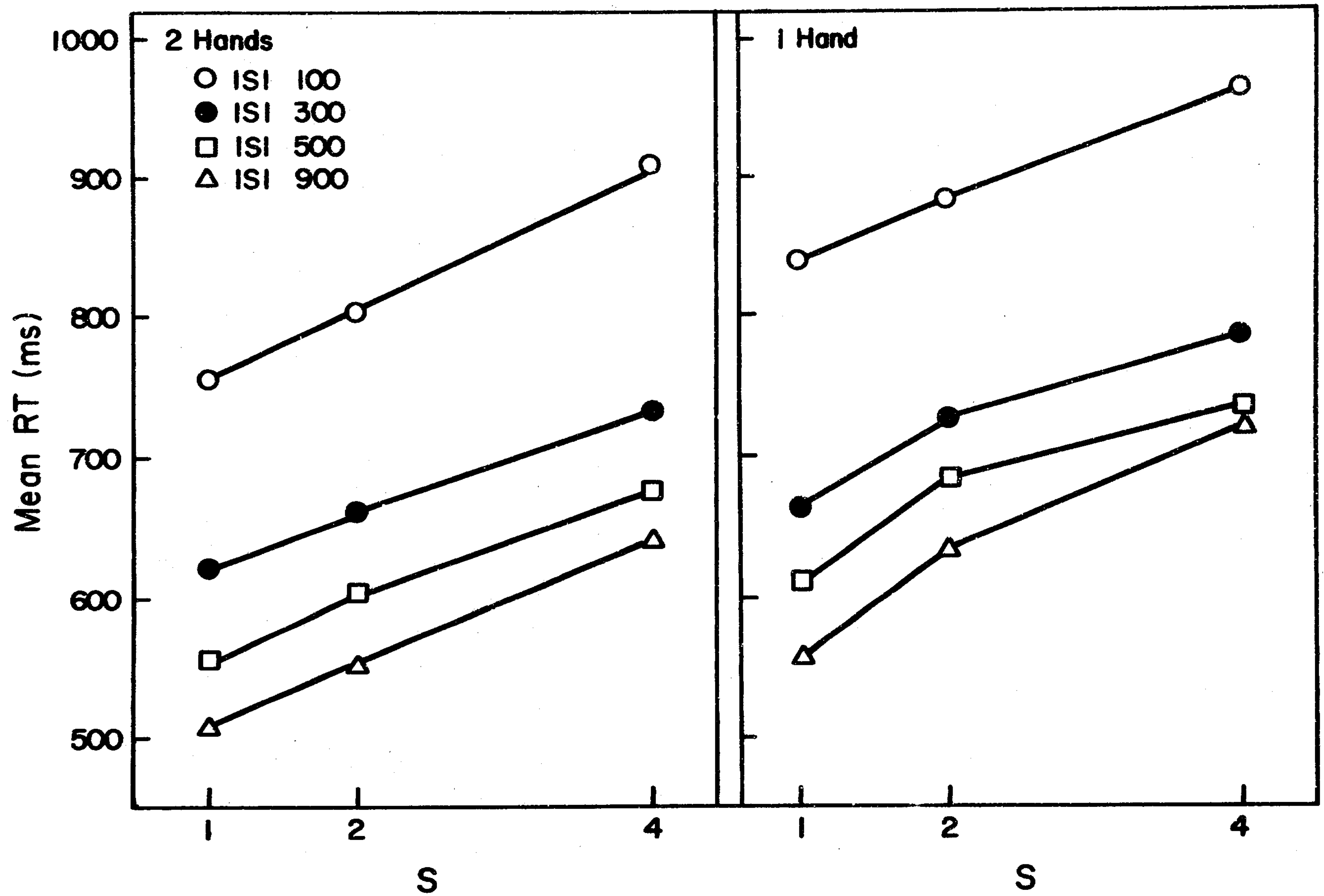

Figure 12 - Mean reaction time in the character classification task as a function of memory load, plotted separately for each ISI and response condition.

of Fig. 12, it is possible to determine whether the time-sharing decrement and the effects of response discriminability are localized within a single information processing function or represent variations in two independent functions. This is done by testing the interaction between ISI and response discriminability. In the present data this interaction did not approach significance, $F(3, 138) < 1$. The maximum time-sharing effect in the one-hand condition was 259 msec, and 255 msec in the two-hand condition. Hence, the effects of ISI and response discriminability are additive, which would lead one to conclude that two independent processing functions are being manipulated by these variables. Logic suggests the locus of the response discriminability effect must be the process of response selection. The remaining process contributing to the intercept value of the functions in Fig. 12 is stimulus encoding, hence, by a process of elimination, the time-sharing effect must be localized in the stimulus encoding function.

In order to confirm this conclusion another experiment is required in which signal-to-noise ratio is varied in order to influence the stimulus encoding process directly. If the time-sharing decrement is in fact localized in encoding, then the effects of ISI and S/N ratio should interact. Unfortunately, this experiment could not be done within the period of this grant, and so we are led to the conclusion that the sequential demand effect is localized in the stimulus encoding function by a process of elimination based on the results of Experiment XI. It is worth noting, however, that the same conclusion was reached in Experiment VII under experimental conditions markedly different from the present experiment, although still within the sequential demand paradigm. Furthermore the effects of simultaneous demand time sharing on shadowing performance in Experiment II led us to the same conclusion. Finally, Briggs (1971), in a related program of research, made extensive use of the binary classification paradigm in studying simultaneous demand time sharing and he also was led to the conclusion that the time-sharing decrement is localized primarily in the process of stimulus encoding.

EXPERIMENT XII: RESPONSE VARIABLES IN THE PSYCHOLOGICAL REFRACTORY PERIOD PARADIGM
(H. G. Shulman and A. G. Greenwald)

The twelfth experiment to be reported was actually conducted in parallel with Experiment XI and represented an effort to converge on response factors as the locus of the time-sharing decrement observed in the sequential demand paradigm, using a different set of operations from those chosen for Experiment XI. Greenwald (1970) has distinguished between two forms of compatibility relationships that may characterize the mapping of stimuli onto responses in a choice RT experiment. The first has traditionally been referred to as S-R compatibility (Fitts and Seeger, 1953) and refers to the logical relationship between elements in a stimulus display and their corresponding responses in a response device. High S-R compatibility might be represented by a

direct spatial correspondence (e.g., leftmost response button assigned to leftmost stimulus light), or by a direct logical correspondence (e.g., move a lever to the left when the stimulus is the word "left") The second type of compatibility distinguished by Greenwald is called Ideomotor (IM) compatibility. High IM compatibility arises whenever a stimulus resembles the sensory feedback generated by its assigned response. Thus making the vocal response "left" to an auditory presentation of the word "left" is IM compatible. However, neither making a leftward movement of a lever in response to the spoken stimulus "left," or speaking the word "left" in response to a visual presentation of the word "left," is regarded as an instance of high IM compatibility, although they are such instances of high S-R compatibility. Greenwald has produced evidence to show that RT is faster for high IM compatible events than for high S-R compatible events. The difference between the two being due to the greater facilitation of the response selection process afforded by an event high in IM compatibility, where the stimulus actually resembles the response required.

In Experiment XII we compared the effects of S-R and IM compatibility on the time-sharing decrement observed in the PRP experiment. Both task 1 and task 2 compatibility were manipulated. Our expectation was that when both tasks were S-R compatible the PRP decrement would be greatest, and when both were IM compatible the decrement would be minimized. Conditions in which one of the two tasks was IM compatible, the other S-R compatible, were expected to fall in between these extremes.

Method

The events on each trial of the experiment proceeded as follows: First, a visually presentation of the task 1 stimulus occurred. A manual response, moving a lever either to the left or right, was required to this stimulus. After an ISI ranging from 0 to 1000 msec the auditory task 2 stimulus occurred, this event requiring a vocal response. The independent variables were (1) ISI (0, 100, 300, 500 or 1000 msec), varied in blocks of 120 trials within Ss, and (2) the compatibility relationship characterizing tasks 1 and 2. The compatibility relationship for either task could be either high S-R compatibility or high IM compatibility, and four between S conditions (n = 10 per group) were defined by the factorial combination of the two compatibility types with first and second task. S-R compatibility in the first (visual) task was provided by using as stimuli the printed words "left" and "right" for which the appropriate responses were movement of a lever to the left or right. IM compatibility for task 1 was provided by using as stimuli an arrow pointing to the left or the right, and requiring movement of the lever in the direction indicated by the arrow. For task 2 (auditory stimulus), high S-R compatibility was provided by using the spoken words "A" or "B" as stimuli and requiring the vocal responses of "one" or "two," respectively. High IM compatibility in the second task was provided by requiring the vocal responses "A" and "B" to the spoken stimuli "A" and "B."

Results

Figure 13 shows mean RT for the second task separately for the four conditions defined by first and second task compatibility conditions. The main effect of ISI was significant, indicating the presence of the PRP or time-sharing effect. The main effect of compatibility condition was also significant as was the interaction between ISI and compatibility type. The main effect of compatibility condition simply reflects the facilitation afforded performance by IM compatibility as compared to S-R compatibility. The interaction effect provides us with information about the nature of the time-sharing decrement. Table VII shows the magnitude of this decrement in each condition, measured as the difference between RTs at ISI = 0 and ISI = 1000 msec.

Table VII. Mean RT (in msec) in Each Condition at the Two Extreme Interstimulus Intervals

Condition	ISI = 0	ISI = 1000	Decrement
SR-IM	453	310	143
SR-SR	703	538	165
IM-IM	415	325	90
IM-SR	559	470	89

Notice first that similar time-sharing decrements occur when first task compatibility type is held constant. That is the time-sharing decrement observed in second task performance does not vary as a function of second task compatibility type. Since compatibility type is taken to influence response selection this result seems to confirm the results of Experiment XI in that variations in response selection effects do not interact with the time-sharing decrement.

The time-sharing decrement shown in Table VII was reduced by a factor of roughly 40% when the first task was IM compatible as opposed to S-R compatible. This finding reflects the fact that first task RT was significantly faster for the IM compatible conditions, hence there was less processing overlap between the two tasks when task 1 was IM as opposed to S-R compatible. It is a general finding in the literature on the PRP effect that the task 2 decrement is related to the magnitude of first task RT at any given ISI.

EXPERIMENT XIII: DIVIDED AND SELECTIVE ATTENTION IN A CHARACTER CLASSIFICATION TASK: SIMULTANEOUS DEMAND TIME SHARING (H. G. Shulman and J. Hayes)

The final experiment to be reported marked a return to the simultaneous demand time-sharing effect studied in our earlier experiments.

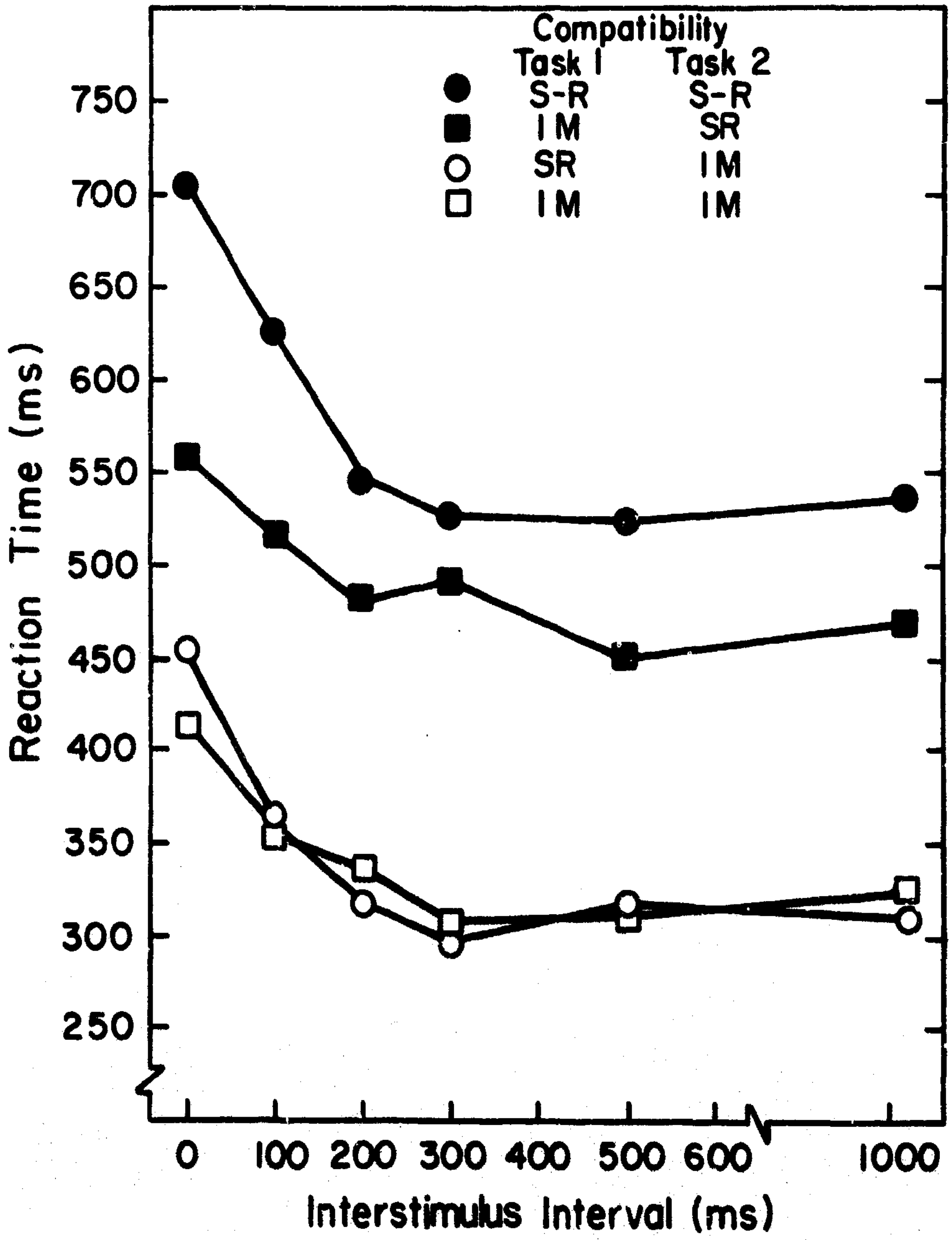

Figure 13 - Mean RT for the second task (auditory stimulus-vocal response) on each trial as a function of ISI, plotted separately for each compatibility condition.

Experiment XIII had three purposes. The first was to demonstrate that the sequential and simultaneous demand time-sharing decrements are related phenomena. This, of course, has been our assumption throughout this program of research, and it was felt that an empirical demonstration of this similarity would be useful. The second was to develop a method for studying successive demand time sharing in the character classification task used in Experiments IX and XI to study sequential demand time sharing. And the third was to investigate the ability of the S to filter irrelevant information out of the physical stimulus when instructed to do so, and to compare performance under these instructions to performance in the same stimulus conditions with instructions to time share.

Method

The character classification task used as task 2 in Experiments IX and XI was used in the present experiment. Target set sizes of s = 1, 2, or 4 numerals were used. In addition to set size the independent variables were the presence vs. absence of a background color on the numeral display, and the requirement to either process or ignore background color when present.

Prior to each block of 24 trials the target set was presented to S for memorization. A series of single numerals followed, each of which was classified as either belonging ("yes" response) or not belonging ("no" response) to the target set. For a given block of trials the background of the display either remained gray or changed randomly from red to green from one trial to the next. In the conditions having a chromatic background for the test numerals the display was gray at all times except when the numeral was presented. Hence color information was only available while numeral information was present. Two groups of 24 Ss differed in terms of the instructions given them with respect to their treatment of the color information on trials where such information was present. The first, or selective attention group. was instructed that the color information was irrelevant to their task, and that they should ignore it. It is worth noting that the numeral was superimposed on the colored ground, so that the instructions to ignore color could not be executed by simply not looking at the color. The second group was given divided attention instructions, which were to note the color that appeared with the numeral and report it verbally to the experimenter on each trial, after having responded to the numeral. Thus time sharing was required in the sense that stimulus information for two tasks (numeral classification and color memory) was available simultaneously, but simultaneous responding was not required, and in fact was actively discouraged.

Results

Figure 14 presents the major results of Experiment XIII. The two functions drawn with solid lines are the data from the control (gray background) condition in each of the two groups (selective vs. divided

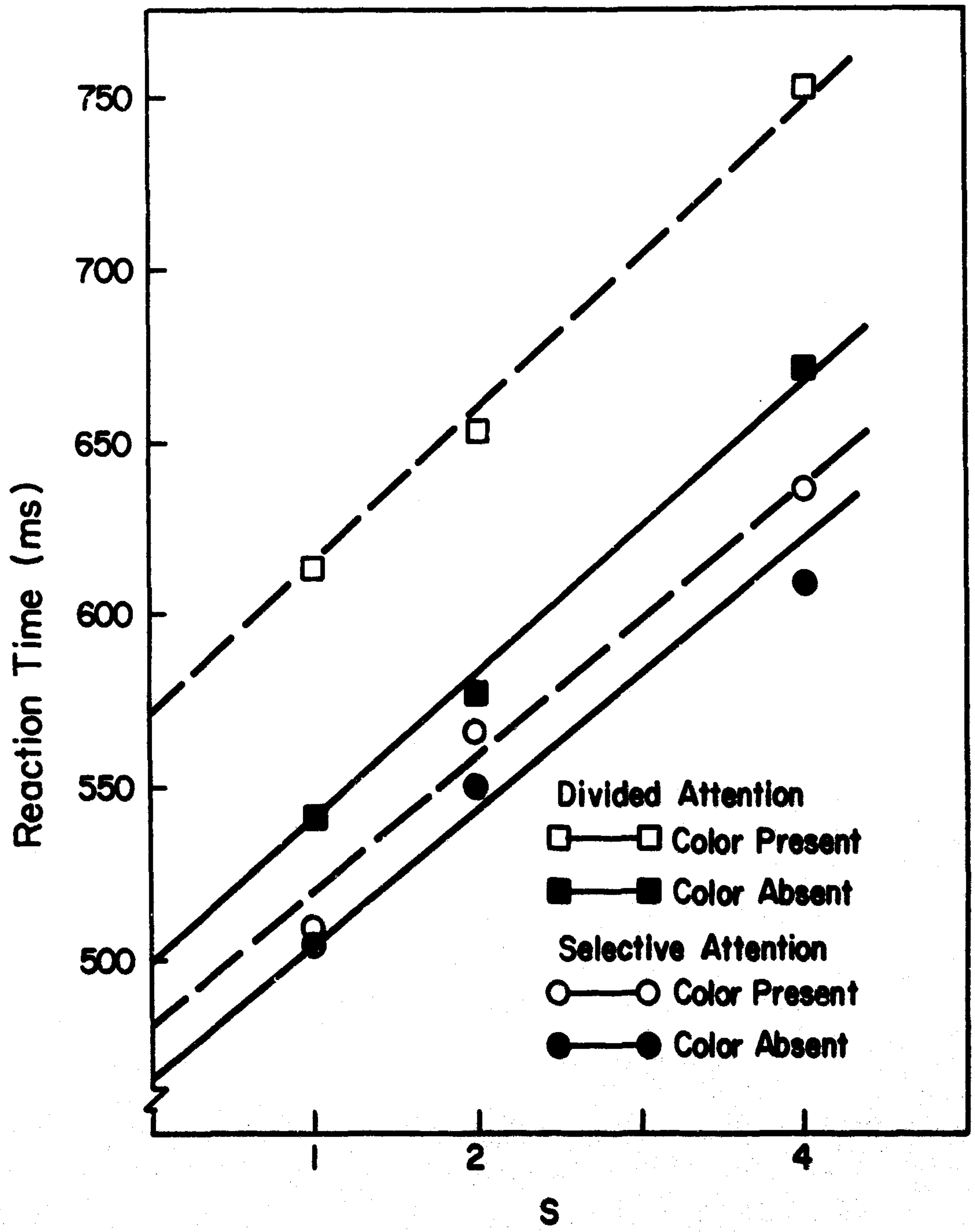

Figure 14 - Mean RT for character classification as a function of target set size (S), plotted separately for divided and selective attention condition and their respective control conditions.

attention). The difference between these two functions is probably due to individual differences in the subject samples assigned each group, since the experimental treatment in the control condition was identical for the two groups. The simultaneous demand time-sharing effect appears as an intercept difference of approximately 75 msec between the control function for the divided attention group and the function for trials on which color information was present. The selective attention instruction was effective in reducing this decrement, the intercept difference being only 15 msec.

The results may be compared to the results of Experiment VII which dealt with the effects of sequential demand time sharing on RT. In Experiment VII an effect of time sharing on stimulus encoding was obtained which amounted to a maximum decrement in RT of about 65 msec. This is approximately the magnitude of the present decrement. For this reason and because the task structure of the present experiment was unlikely to result in interference with response selection, one must attribute the present simultaneous demand decrement to the stimulus encoding process. More generally, the similarity of the functional relationships obtained when choice reaction time is used to study simultaneous and sequential demand time sharing lends empirical support to our basic assumption of a theoretical similarity between the two time-sharing paradigms.

SUMMARY

The two-year program of research summarized in the present report has focused on two basic time-sharing paradigms, labeled simultaneous demand and sequential (or successive) demand. The differences between these two paradigms are easily maintained on an operational level. However our research in the two paradigms leads us to conclude that the time-sharing decrements observed in the two situations reflect similar underlying processes. The major locus of the time-sharing decrement in situations where memory capacity is not exceeded appears to be stimulus encoding.

In those experiments where task demands placed a heavy load on short-term memory, we found evidence that would indicate the loci of the time-sharing decrement to be in the process of stimulus encoding and in the process by which information is transferred from short- to long-term memory. In the current literature on memory this transfer process is often characterized as a recoding operation in which information is extracted from short-term storage, recoded, and transferred to long-term storage. Note the similarity between this conceptualization and the process of stimulus encoding in which information is extracted from the physical stimulus (or a brief sensory trace thereof), coded, and transferred either to short- or long-term storage. In terms of a computer program these two functions, encoding and recoding, might very

well be handled by the same sub-routine. One might speculate, then, that the two loci of the time-sharing decrement identified in this research are actually reducible to a single function in the processing chain: The function that moves and translates information, and in fact if we were to give this function a label it would not be inappropriate to simply refer to it as the attention mechanism.

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